Changes in peripheral refraction, higher order aberrations, and accommodative lag with a radial refractive gradient contact lens in young myopes

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Short title: Radial Refractive Gradient Contact Lens in Myopia

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ABSTRACT

Objective: To evaluate changes in the peripheral refraction (PR), visual quality, and accommodative lag (LAG) with a novel soft radial refractive gradient (SRRG) experimental contact lens that produces peripheral myopic defocus.

Methods: Fifty-nine myopic right eyes were fitted with the lens. The PR was measured up to 30 degrees in the nasal and temporal horizontal visual fields and compared with values obtained without the lens. The LAG was measured monocularly using the distance-induced condition method at 40 cm, and the higher order aberrations (HOAs) of the entire eye were obtained for 3- and 5-mm pupils by aberrometry. Visual performance was assessed through contrast sensitivity function (CSF).

Results: With the lens, the relative PR became significantly ($P<0.05$) less hyperopic from 30 to 15 degrees temporally and 30 degrees nasally in the M and J0 refractive components. Cylinder foci showed significant myopization from 30 to 15 degrees temporally and 30 to 25 degrees nasally ($P<0.05$). The HOAs increased significantly, the CSF decreased slightly but reached statistical significance for 6 and 12 c/d ($P<0.05$), and the LAG decreased significantly with the SRRG lens ($P=0.0001$). There was a moderate correlation between HOAs and CSF at medium and high spatial frequencies.

Conclusion: The SRRG lens induced a significant change in PR, particularly in the temporal retina. Tangential and sagittal foci changed significantly in the peripheral nasal and temporal retina. The decreased LAG and increased HOAs particularly in coma-like aberration may positively affect myopia control. A longitudinal study is needed to confirm this potential.

Key Words: Accommodative lag--Multifocal contact lens--Myopia--Peripheral refraction.

Myopia should no longer be considered simply as a refractive problem.[1] Myopic eyes are prone to a number of ocular pathologies, such as retinal degeneration and glaucoma.[2] Myopia should be viewed as a progressive condition associated with the potential risk of visual loss. Moreover, the prevalence of myopia is increasing in Asian urban regions where 80% of teenagers are myopic.[3] Myopia management has a high impact on public health; finding effective strategies to slow myopia progression should be a priority.

A variety of optical devices and visual strategies have been developed to address central vision but with a reduced or limited effect. For example, undercorrection actually increases the rate of myopia progression.[4–6] Bifocal and multifocal lenses have a limited effect.[7] Some studies have shown promising results in children with rapid myopia progression, with higher success in patients with esophoria at near and higher accommodative lag (LAG).[8] Underaccommodation, i.e., LAG, is quantified as the difference between the dioptric level of the accommodative stimulus and the measured accommodative response. Larger LAG, in association with near work, which induces retinal blur, has been proposed as a factor in myopia development and progression.[9] Although progressing myopes show larger LAG,[10] attempts to slow myopia progression through plus lens correction at near to reduce or eliminate LAG have obtained only modest results in children.[11] Otherwise, a recent study related retinal superior myopic defocus induced by progressive addition lenses (PALs) with less central myopia progression.[12]

Orthokeratology (OK) is currently the most effective optical method to slow myopia progression.[13–17] Several authors have shown the great impact of OK on the peripheral retinal image,[18,19] with movement of the peripheral image shell forward, which was described as the cause of the myopia control effect.[20] Peripheral hyperopic refraction is believed responsible for myopia development, as the ocular growth mechanism tries to compensate for the imposed peripheral defocus with further elongation even in the presence of a perfectly focused central image.[21,22] There has been increased interest in peripheral refraction (PR) after animal studies showed an emmetropization response to specific visual manipulation, with myopia being the result of both spatial form deprivation and imposed hyperopic defocus.[23] The peripheral retina itself can recover or induce myopia,[24,25] especially in monkeys, indicating that the emmetropization process may be controlled actively by the optically modified peripheral image.[26] Myopic eyes have greater relative peripheral hyperopia,[27–29] a characteristic that appears about 2 years before the onset of myopia. [30]

Despite evidence in animals, unfortunately, some studies in humans have shown that baseline PR does not predict or play a significant risk factor in the subsequent onset of myopia or affect myopia progression[31,32]; it had been proposed that the peripheral error profiles in myopes may merely be a consequence of ocular growth rather than have a causative role.[33] However, some correlation between changes in PR and central shift has been found in the nasal visual field,[34] and stable and progressing myopes had significantly different characteristics in their peripheral retinal shape and astigmatic components of tangential and sagittal power errors.[35]

Another theory for myopia onset is related to optical higher order aberrations (HOAs). Some investigators have tried to gain an understanding of the role of optical quality changes by OK in reducing the rate of axial growth. Eyes with less axial elongation over the treatment period had a greater increase in coma-like aberrations.[36] Despite the authors' statement, that study did not link both findings. Other HOAs, especially spherical aberration (SA), have been related to LAG; when the eye is choosing the best image plane[37] myopes generally are less sensitive to negative than positive defocus, which can be linked to their HOA pattern.[38]

According to the peripheral hyperopic defocus theory for myopia control, several approaches have used soft contact lenses with modified optics to change the PR and the myopia progression was arrested by from 34%[39] to 50%,[40] indicating that the treatment effect was correlated with wearing time.[41] Analyses of the optics of the monofocal and bifocal lenses[42,43] and related PR changes have been reported,[44] but no studies have shown that the changes in LAG and HOAs were correlated with the changes in PR induced by a radial refractive gradient (SRRG) contact lens intended to arrest ocular elongation.

The aim of the current study was to simultaneously evaluate the effect of a SRRG contact lens on PR, LAG, whole eye HOAs, and contrast sensitivity in a population of young myopes. To our knowledge, this is the first study to address these three important factors of the theories and justify optically guided regulation of ocular growth in one study.

METHODS

Sample

Sixty-two subjects were recruited from among the students at the Terrassa School of Optics and Optometry in the Universitat Politècnica de Catalunya, Terrassa, Spain. After three subjects were excluded because of contact lens decentration, 59 subjects (29 men, 30 women) were evaluated. The inclusion criteria were myopia with a spherical equivalent (SE) refraction ranging from -0.50 to -7.50 diopters (D) (mean ± standard deviation [SD], -2.44 ± 1.71 D) and refractive astigmatism below -0.75 D (-0.19 ± 0.33 D), ages between 18 to 25 years, and best-corrected visual acuity (BCVA) of 20/20 or higher. The exclusion criteria were any ocular disease or use of any systemic or ocular medication that could affect the refractive error or accommodative function. Subjects were required to understand and sign a consent form before study enrollment. The ethical committee of clinical research of the Teknon Medical Center, Barcelona, Spain, approved the study protocol, which adhered to the tenets of the Declaration of Helsinki.

Lens

An experimental SRRG lens designed to produce peripheral myopic defocus was fitted after a baseline measure was obtained without refractive correction. The lens is comprised of 2-hydroxyethyl methacrylate, with 38% water content (overall diameter, 14.00-15.00 mm; base curve radius, 8.00-8.90 mm). The central thickness varied depending on the optical power of the lens.

The optical design of the experimental lens used parameters for theoretical eyes obtained from Atchison[45] that were incorporated into the Zemax-EE software version 6 (Radiant ZEMAX, Redmond, WA, USA). The experimental lens has a unique central front and back aspheric optic zone 8 mm in diameter. The lens has a radial refractive gradient, so only the central apical zone has the power required for distance vision, and the aspheric design provides a progressive increasing add power, starting at the central geometric point and providing a +2.00 D add plus power 1.9 mm from the center (3.80-mm chord diameter) corresponding to about 30 degrees of retinal eccentricity and achieving about +9.5 D at the edge of the optical zone (8 mm chord diameter). The contact lens was fit according to the subjective refraction, corneal curvature, and visible iris diameter. The corneal topography was measured using the Pentacam (Oculus, Wetzlar, Germany). Adjustments to the final prescription were based on spherical overrefraction and a new lens was ordered if discrepancies over ±0.25 D occurred. Fitting was assessed for centration and LAG on lateral gaze movements using the slit-lamp beam. All lenses were within the desired limits of less than 0.25 to 0.50 mm of decentration on blink in upgaze and 0.50 to 1.00 mm LAG of horizontal excursion on lateral gaze. These values are considered acceptable good fitting parameters for modern soft contact lenses.[46] During the study visit, the lenses were allowed to settle for 20 to 30 minutes to equilibrate and stabilize on the ocular surface and for subjects to feel sufficiently comfortable to undergo the examination. Measurements were obtained without correction for PR and aberrations and with the best spectacle correction in a trial frame at 12 mm for CSF.

Peripheral Refraction

Measurements of the central and peripheral (off-axis) refractions were obtained with an open-field Grand Seiko Auto-Refractometer/Keratometer WAM-5500 (Grand Seiko Co., Ltd., Hiroshima, Japan) up to 30 degrees in the nasal and temporal horizontal retina in 5-degree steps. This instrument and its other commercial brand that uses the same technology for refractive error measurement (Shin-Nippon) have been used reliably for foveal[47,48] and PR measurements.[49,50] In the current study, a laser system was mounted on the subject’s head and aligned with the central fixation point in primary gaze. The PR was measured with head rotation to ensure that the lens did not move from the resting position in primary gaze. To measure head rotation, the laser had to coincide with a series of markings on the wall 2.5 meters in front of the subject. This created a limitation on the range of field measured, making it measureable up to 30 degrees. The left eye was occluded during the measurements to avoid misalignments under binocular fixation. Measurements were conducted under noncycloplegic conditions. Descriptive statistics (mean ± SD) were calculated for the refraction vector components

$M = Sph + Cyl/2$, $J0 = -Cyl \cdot \cos(2\alpha)/2$, and $J45 = -Cyl \cdot \sin(2\alpha)/2$ according to Fourier analysis, as recommended by Thibos et al.,[51] where Sph, Cyl and α are the manifest sphere, cylinder, and axis, respectively. Sagittal and tangential foci were calculated according to the following equations: $Fs = M - J0$ and $Ft = M + J0$. Peripheral measurements were done using the pupillary center for alignment. M, J0, and J45 were calculated from the mean clinical refraction resulting from five consecutive readings obtained at each visual field eccentricity and were considered for statistical analysis. The relative PR error (RPRE) was calculated by subtracting the central M, J0, or J45 value obtained at the fovea from that obtained at each eccentric retinal location.

LAG

The LAG was measured monocularly in the right eye using the Grand Seiko WAM-5500 autorefractor through the SRRG lens at distance and near for a target consisting of a line of a high-contrast reading card of 20/40 letters. The near stimulus was placed at 40 cm, which represents a 2.50-D accommodative demand. The letter size at near was changed to keep the visual angle the same as the target at 2.50 meters. The luminance was 20 cd/m^2 for both targets. Five readings were measured in each position, and during the measurements the subject fixated on one letter target. The sphere and cylinder were recorded for each measurement, and then the mean SE for the set of measurements was calculated. The LAG was calculated by subtracting the mean measured accommodative response from far to near SE for near and then subtracting it from the accommodative stimulus following the procedures described by He et al.[52] Sustained accommodative effort has been suggested as a potential etiological factor for myopia progression.[53]

Optical Quality

The optical quality of the eye was assessed using an Irx3 Hartmann-Shack aberrometer (Imagine Eyes, Orsay, France). HOAs from the third to sixth order were obtained under dim light under natural mydriasis with a 5-minute adaptation time to assure the largest natural pupil, and a limitation for 3- and 5-mm pupillary sizes was done using the software in the instrument. Changes in the root mean square (RMS) from baseline without the lens for spherical-like HOAs (including Zernike polynomials Z_4^0 and Z_6^0), coma-like HOA (including Zernike polynomials Z_3^{-1}, Z_3^1, Z_5^{-1}, and Z_5^1), trefoil (including Zernike polynomials Z_3^{-3}, Z_3^3), secondary astigmatism HOA (including Zernike polynomials Z_4^{-2}, Z_4^2, Z_6^{-2}, and Z_6^2), and total HOAs were considered for statistical analysis.

Visual performance was assessed through the contrast sensitivity function (CSF) using a CVS-1000 E (VectorVision, Dayton, OH) for spatial frequencies of 1.5, 3, 6, 12, and 18 cycles/degree (c/d) with the patient at 3 meters under photopic (105 cd/m^2) and low mesopic (0.6 cd/m^2) conditions.

The VA was measured with the Logarithmic 2000 series Early Treatment Diabetic Retinopathy Study chart at 4 meters (Precision Vision, La Salle, IL, USA).

Statistical Analysis

The SPSS software package version 17 (SPSS Inc., Chicago, IL, USA) was used for statistical analysis. The Kolmogorov-Smirnov Test was applied to evaluate the normality of the data distribution. The paired Student’s t-test or Wilcoxon signed-rank test for two-related samples was used to analyze the statistical significance of the differences between contact lenses vs. baseline depending on the normal or non-normal distribution. The

Pearson or the Spearman rho correlation tests also was used to determine the relationship between aberrations and CSF. $P<0.05$ was considered statistically significant.

RESULTS

Relative Peripheral Refraction

The RPRE mean values expressed as M, J0, J45, sphere, and cylinder, respectively, induced significant differences compared with baseline in the peripheral retina from 30 to 15 degrees temporally and 30 degrees nasally in the M value, from 30 to 20 degrees temporally and 30 degrees nasally in J0 (with a significant opposed value at 15 degrees nasally), all J45 values, significant values from 30 to 20 degrees temporally in sphere and from 30 to 15 degrees temporally and from 30 to 25 degrees in the nasal retina (with a significant opposed value at 10 degrees nasally) in cylinder foci. Myopization increased with eccentricity in these values that corresponded to the difference without lenses and with the experimental contact lens used in the study. Table 1 shows the specific values.

VA and CSF

Comparison of the VAs with and without lenses showed no significant ($P=0.0999$) difference in either condition, indicating that the experimental lenses had no effect on the VA.

The CSF differed significantly in the 6 c/d frequency under photopic conditions, with a loss of -0.08 ± 0.25 (log) with the experimental lens ($P<0.05$). The scotopic conditions resulted in a significant sensitivity loss at 6 and 12 c/d (mean difference, -0.15 ± 0.25; $P<0.05$ and -0.14 ± 0.29; $P<0.05$ log units, respectively) (Table 2).

Aberrations

All HOAs including trefoil, coma-like, SA, secondary astigmatism, increased with the SRRG lens compared with no lens (*P*<0.05). This effect was particularly marked for the 5-mm pupillary size rather than the 3-mm pupils. Significant differences were seen with the SRRG lens for the 3-mm pupil compared with baseline and for the 5-mm pupil (*P*<0.05 for all orders of aberration). The third ($Z_3^{1.}$ and Z_3^{-1}) and spherical-like RMS (Z_4^0 and Z_6^0) showed the largest differences (Fig. 1).

SA and CSF relations

We obtained a significant correlation between SA and CSF at 3 mm pupil diameter for the following spatial frequencies: 3c/d (r= -0.308; p<0.05), 6 c/d (r=-0.545; p<0.001), 12 c/d (r= -0.495; p<0.001) and 18 c/d frequency (r= -0.420; p<0.005) and Secondary Astigmatism we found a weak significant correlation (r=-0.281; p<0.05). On 5 mm pupil conditions results showed a significant correlation for all the CSF frequencies: 3 c/d (r= -0.371; p<0.05), 6 c/d (r=-0.423; p<0.005), 12 c/d (r=-0.463; p<0.001), 18 c/d (r=-0.478; p<0.0001), and SA. Coma had a significant correlation for 6 and 12 c/d (r=-0.347; p<0.05 and r=-0.377; p<0.005) and Secondary Astigmatism for the frequencies of 12 and 18 c/d (r=-0.369; p=0.008 and r=-0.311; p<0.05) respectively.

LAG

With the lens on the eye, the accommodative lag decreased significantly (*P*=0.0001) compared with no lens. The mean values with and without the lens were 0.37±0.42 and 0.64±0.28 diopter, respectively. The difference between the means (0.28±0.40 D) was larger than the minimal amount in clinical situations.

DISCUSSION

The experimental SRRG contact lens modified the peripheral refractive shell profile by moving it forward in the young myopic eyes in the current study. A study of a large sample of children with myopia reported a mean of +0.80 ± 1.29 D for the relative hyperopic PR at 30 degrees in the temporal peripheral retina.[54] Therefore, the change we found in the M value of -1.07 D at 30 degrees axis in the peripheral temporal retina (nasal visual field) may be sufficient to modify the position of the image shell, placing it in front of the retina in this area.

We observed significant differences between the naked eye and when the SRRG lens was worn in the SE (M) value measurements at 30, 25, 20, and 15 degrees in the temporal retina but only at 30 degrees in the nasal retina.

LEGENDS

FIG. 1. Higher-order aberrations (HOAs) without the lens and with the experimental soft radial refractive gradient lens expressed as trefoil, spherical-like aberrations, coma-like aberrations, secondary astigmatism and HOA for 3- and 5-mm pupillary sizes.

shows the mean ± SD relative peripheral SE at each retinal location. One reason for this result may be related to a normal tendency for soft lenses to move temporally off-center in addition to the visual axis nasal position in respect to the optical axis (angle kappa). Wolffsohn et al. reported mean lens decentration of 0.07± 0.14 mm horizontally (temporal) compared to the center of the cornea,[46] and Dominguez-Vicent et al. reported a normal angle kappa value of 0.43±0.13 mm using the Orbscan (Bausch & Lomb, Rochester, NY, USA).[55] The sum of the two accounts for the temporal position of the optical center of the lens respects the optical axis, which may correspond to between a 6- to 10-degree axis error depending of the eye model used.[56-58] In other words, usually a progressive center distance soft lens induces more addition power on the temporal retina because of this decentration effect and might explain the bigger effect of the temporal retina also reported previously.[39,59,60] Moreover, a recent study of new soft contact lens for myopia control designed evaluated a lens with a decentered optical zone that was shifted 0.5 mm nasally from the geometrical center of the lens to be coincidental with the optical center of the lens with the pupillary center. Results on myopia control with this lens did not reach significance, perhaps because of the lower peripheral progressive addition of +0.50 D and no change in the peripheral refraction.[61] A possible misallocation error due to the head of the patient when looking at the fixation point could be avoided by turning the eye only as a recent study[62] has shown that when two multifocal lenses were tested and the horizontal visual field, values did not change significantly when measured during rotation of the eye or head.

The nasal half of the retina may be more important regarding the mechanism of ocular growth control since Faria-Ribeiro et al. reported a difference between a progressing and a nonprogressing group of young myopic subjects; the patients in the progressing group had more hyperopic relative astigmatic defocus than the nonprogressing group in the nasal retina.[35] If the peripheral retina is responsible for the ocular growth changes, the relationship between the blur for the "tangential" and "radial" neurons may control growth.[38] The blur detected for these neurons differs due to oblique astigmatism, which places the foci lines close to the vertical and horizontal meridians.[63] In this sense, we found a significant difference in the astigmatic component J0 but not in J45 such as that seen in Fig 3A and B, respectively.

Indeed, in the peripheral retina oblique astigmatism increases and produces two main foci lines. Looking at both astigmatic foci (sagittal and tangential), we observed that the lens significantly changes the peripheral astigmatic refraction toward more myopia in the temporal retina (from 30 to 15 degrees in the temporal retina and from 30 to 25 degrees in the nasal retina) (Fig .4). The sagittal focus remains hyperopic for most of the peripheral visual field even while the lens is worn. Similar results have been found recently in OK patients, particularly in lower myopes.[64] Howland proposed that astigmatism acts as a unique visual cue,[65] but its role remains unclear. Adding to this uncertainty is the potential effect of different types of off-axis astigmatism on the central refraction.[1,66] However, in the presence of two focal lines, the retina tends to use the more myopic of the two lines to guide eye growth. In monkeys treated with dual-focus lenses, refractive development was dominated by the more anterior (i.e., relatively myopic) image plane. In this respect, a series of studies have shown that myopic defocus appears to have a stronger effect on ocular growth than hyperopic defocus.[67] The results in monkeys with imposed dual-focus lenses were images formed at two distinct planes across the entire central retina, indicating that imposing relative myopic defocus directed refractive development in most cases toward the more myopic/less hyperopic focal plane (i.e., the more anterior focus).[68] This seems to agree with the results found in orthokeratology where myopization effect is mainly obtained at the expense of the tangential focus.[64] Otherwise, if the more emmetropic astigmatic plane is preferred, the consolidated efficacy of OK to regulate myopia progression[69] could not be justified.

We need to be aware that a decentered optical zone may increase optical multifocality since this places in front of the pupil greatly different power zones of the lens that increase aberrations, mainly coma. In the current study, we found that the lens significantly increased the coma-like, SA, secondary astigmatism, and total HOAs. We reported similar results with a previous soft peripheral gradient design using the same concept.[70] According to another previous experiment that we conducted, the design of the current lens manufactured with a rigid gas-permeable material caused even stronger changes in peripheral myopization.[71] Among them, the coma-like aberration had a greater change. However, the potential involvement of coma-like aberrations as a regulatory effect over ocular elongation that has been suggested[36] remains to be demonstrated.

Regarding contrast sensitivity, the experimental lens significantly decreased CSF under photopic conditions only at the 6 c/d frequency and worsened all the studied frequencies under scotopic conditions, except for 18 c/d, which remained unchanged. Accordingly, this SRRG treatment lens degrades the foveal image especially in dim light. Nonetheless, because the VA was measured under photopic conditions and for high contrast charts, we did not observe a decrease in VA. We found a significant negative correlation between the SA and CSF without lenses at 6, 12, and 18 c/d in 3- and 5-mm pupils but no correlation between the HOAs induced by the lens and CSF. This may be related to a particular change in the HOAs for each individual. Moreover, it may suggest that the associated reduction in image quality may promote axial myopia in a way similar to form deprivation, which is a graded phenomenon.[72] However, the results of animal studies with multifocal or dual-focus lenses indicated that instead of a resulting reduction in image contrast the lenses slow axial grow.[73]

Finally, we found a significant reduction in LAG (Fig. 5). In fact, some studies have shown that induced changes in ocular SA by OK decrease the LAG,[37] in contrast with other investigators who found no change[74] possibly due to different methodology.

Lead and LAG of accommodation are affected by ocular HOAs, with significant correlations with the peak of the visual Strehl ratio based on the modulation transfer function.[75] It seems plausible that the higher LAGs seen in myopes provide optimized retinal image characteristics.[76] Visual contrast is greater when Zernike coefficients C_2^0 and C_4^0 of the eye and lens system have opposite signs. A positive SA combined with myopic blur reduces the LAG placing the best plane image in front of the retina.[38,77] Because the amount of positive SA declines with accommodation and becomes steadily more negative with further accommodation,[78] the increase in positive SA with the current lens may protect against negative SA and hyperopic blur that will situate the best plane image behind the retina, resulting on a higher LAG and worsening the peripheral defocus.[77] A limitation of the current study was that we did not measure the SA under accommodation to validate this theory.

High LAG is considered a factor in the pathogenesis of myopia because of the association between myopia progression and near work.[79] Further analyses with PALS and bifocal lenses showed larger treatment effects in individuals with larger LAGs in combination with near esophoria.[80,81] Moreover, larger LAGs have been linked to development[82] and progression of myopia.[83] While there is no unanimous agreement across studies, some have indicated a tendency for myopic children to have a larger LAG compared to emmetropes.[80,52] However, hyperopic defocus from LAG, therefore, may be more of a consequence than a cause of myopia.[83]

In conclusion, the SRRG contact lens induced significant changes in the ocular optics by moving the image forward, and especially in the temporal retina. The tangential focus moves to a significantly more myopic location, affecting mainly the temporal retina. The reduction in LAG and increased HOAs may affect ocular growth that requires further studies to establish a causative effect. In this sense, a longitudinal study is needed to clarify the effect of all those factors and their relative weight in myopia progression.

Disclosure

J. Pauné holds the Spanish Patent Application P-2406381 for the lenses evaluated in this study. The remaining authors have no proprietary or financial interest in any of the materials mentioned in this article.

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LEGENDS

FIG. 1. Higher-order aberrations (HOAs) without the lens and with the experimental soft radial refractive gradient lens expressed as trefoil, spherical-like aberrations, coma-like aberrations, secondary astigmatism and HOA for 3- and 5-mm pupillary sizes.

FIG. 2. Relative peripheral refractive error (peripheral minus center) in mean spherical equivalent values (M) as a function of angle in the temporal retina (negative values) and nasal retina (positive values) across 70 degrees of the horizontal visual field. Experimental conditions are represented without the lens (♦) and with the radial refractive gradient (■) lens. The bars represent the standard error of the mean, half of that is suppressed and a polynomial function of second degree was fitted for each experimental situation for a better interpretation of the refractive profile across the horizontal visual field. The black dots indicate the locations with significant (P<0.05) differences.

FIG. 3. Relative peripheral J0 (A) and J45 (B) for both experimental conditions, without the lens (♦) and with the soft radial refractive gradient lens (■). The bars represent the standard error of the mean, half of which have been eliminated for clarity and a polynomial function of second degree was fitted for each experimental situation for a better interpretation of the refractive profile across the horizontal visual field. The black dots indicate the locations with significant (P<0.05) differences.

FIG. 4. Relative peripheral sagittal foci and tangential foci for both experimental conditions without the lens (♦) and with the soft radial refractive gradient lens (■). The bars represent the standard error of the mean, half of which have been eliminated for clarity and a polynomial function of second degree was adapted for each experimental

situation for a better understanding. The black dots indicate the locations with significant (P<0.05) differences.

FIG. 5. Accommodative lag with and without the soft radial refractive gradient lens. Two regression lines are plotted. The dotted line represents no lens and the dashed line represents the experimental lens.